

Economic crossover model between combustion and electric cars

Acquisition cost, energy, maintenance, depreciation by time and use, battery degradation, financing, charging time and lagged adoption

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August modification: incorporation of depreciation by time and use, battery degradation, cost of capital and value of time. Illustrative and parameterised scenario.

CENTRAL IDEA

- The correct comparison is not simply purchase price versus fuel: it is the economic cost of providing mobility over a defined horizon.
- Vehicle capital is consumed in two ways: through calendar ageing/obsolescence and through use. In the EV, the battery adds a measurable dimension through State of Health (SOH) and Equivalent Full Cycles (EFC).
- The 5% financial cost is applied to capital that remains tied up; the base value of time is €15/hour.
- Decision charts use these components jointly. Figures that isolate acquisition or maintenance are deliberately retained as partial diagnostics.

Abstract

This paper proposes an integrated economic model to determine the conditions under which a battery-electric vehicle outperforms an internal-combustion vehicle in mobility cost. The framework distinguishes acquisition price, operating costs, calendar- and use-related depreciation, battery degradation through Equivalent Full Cycles (EFC) and State of Health (SOH), the financial or opportunity cost of capital, residual value, effective charging or refuelling time, and extraordinary risks. The model expresses the break-even point in years, accumulated kilometres and annual utilisation intensity, and represents a multidimensional frontier as a function of access to low-cost charging and the value of time. As an extension from individual choice to market outcomes, it specifies a stylised relationship between economic advantage and the share of new sales with a lag. The main result is methodological: there is no single universal parity date or mileage; the crossover depends on the combination of tied-up capital, usage pattern, energy, depreciation, maintenance, technical degradation and available infrastructure.

Executive summary

This report builds an integrated framework for comparing an internal-combustion vehicle (ICE) with a battery-electric vehicle (EV). The model distinguishes entry price, energy cost, maintenance, economic capital consumption, financial cost, residual value, technical degradation, effective refuelling or charging time and extraordinary risks. From these components it calculates crossovers by years, accumulated kilometres and annual utilisation intensity, and finally links the individual's economic advantage to a stylised market-adoption function with a lag.

With the base parameters used here, the home-charged EV has a five-year economic threshold of approximately 17,218 km/year; slow public charging raises it to about 99,538 km/year; and fast charging, with the assumed price and time, to approximately 194,001 km/year.

For intensive use of 50,000 km/year, the EV's initial liquidity premium is recovered in approximately 2.0 years in the home-charging scenario. Economic TCO, which recognises residual value at each date and capital consumption, may favour the EV before the cash payback point. This is not a contradiction: the two measures answer different questions.

TWO CROSSOVERS THAT SHOULD NOT BE CONFUSED

- Cash payback: when operating savings recover the additional initial outlay. It is a liquidity measure.
- Economic-TCO crossover: when consumed capital cost + operation + financing + time is lower. It recognises that the vehicle retains a residual value.
- An asset can require more cash at purchase and nevertheless consume less economic wealth over the same period.

1. Technical evidence and modelling criteria

1.1. Maintenance: advantages and offsetting effects

An EV eliminates engine oil, spark plugs, fuel filters, the clutch and much of the mechanical complexity of a combustion powertrain. The U.S. Department of Energy estimates in its methodology 6.1 cents/mile of scheduled maintenance for a BEV versus 10.1 for an ICEV [1]. RACE describes the same qualitative direction and also points to lower brake wear because of regenerative braking [2].

Not every component favours the EV. RACE notes that greater weight and immediate torque can increase tyre wear in certain vehicles and driving styles [2]. The model therefore separates time-related maintenance, mileage-proportional maintenance/wear and discrete events. The result is not forced by assuming that 'all maintenance is lower' for the electric vehicle.

1.2. Battery: calendar ageing, cycles and state of health

A battery ages through two mechanisms that should be modelled separately: calendar ageing -time, temperature and state of charge- and cycle ageing -total energy throughput, depth of discharge, charging power and temperature-. Mileage alone therefore does not determine battery health.

The most useful unit for use-related ageing is the Equivalent Full Cycle (EFC): discharging 30% today and 70% tomorrow is approximately one EFC. With a usable 60 kWh battery and billed consumption of 17 kWh/100 km, one EFC corresponds to about 353 km. Thus, 15,000 km/year represents approximately 42.5 EFC/year and 50,000 km/year about 141.7 EFC/year. Under these assumptions, ten thousand EFC would correspond to about 3.53 million kilometres; '10,000 cycles' is therefore not adopted as a typical reference life.

$$EFC = K \times (c_{EV} / 100) / B$$

Real-world data likewise do not support treating 70% or 80% as an automatic replacement point. Geotab, using more than 22,700 vehicles across 21 models, reported in 2026 average degradation of 2.3% per year and an average projection of 81.6% SOH after eight years; high-power fast charging was the most relevant operational factor, with rates close to 3.0% per year versus 1.5% in the lower-power group [3]. Tesla Spain guarantees, depending on version, at least 70% capacity retention for 8 years and 160,000-240,000 km [4]. Euro 7 sets minimum battery-energy requirements for M1 electric passenger cars of 80% up to 5 years/100,000 km and 72% up to 8 years/160,000 km [5]. These thresholds are durability or warranty requirements, not replacement orders.

Cell-level literature shows very wide dispersion by chemistry and operating conditions. An LFP study used here as a cycle-life reference reports at least 2,000-2,500 cycles to 80% capacity in certain applications [6], while other cell tests produce higher figures. The model therefore uses 2,500 EFC to 80% only as a parameterised base calibration, not as a universal physical constant.

2. Model variables and equations

2.1. Three levels of cost

The model distinguishes: (i) acquisition price and liquidity requirement; (ii) monetary/economic TCO; and (iii) generalised cost, which monetises effective time. This separation avoids mixing a cash outlay with the economic consumption of an asset.

$$G_i(t,K) = D_i(t,K) + F_i(t,K) + E_i(K) + M_i(t,K) + C_i^{\text{fixed}}(t) + w \cdot T_i(K) + E[X_i]$$

D is consumed depreciation or economic capital consumption; F is the financial/opportunity cost; E is energy; M is maintenance; C^{fixed} covers insurance, taxes and annual costs; $w \cdot T$ monetises effective time; $E[X]$ captures expected extraordinary repairs or replacements. The purchase price is reflected in D and F and is not added again to economic TCO, avoiding double counting.

2.2. Fixed and use-related depreciation

The underlying intuition -a fixed annual component and another component associated with use- is formalised through economic residual value. For the ICE, the model uses one depreciation rate for calendar ageing/obsolescence and another for mileage. The same structure is applied to the EV as a vehicle, with an additional effect from battery SOH loss.

$$V_{\text{ICE}}(t,K) = P_{\text{ICE}} \cdot \exp[-\alpha_{\text{ICE}} \cdot t - \beta_{\text{ICE}} \cdot K]$$

$$V_{\text{EV}}(t,K) = P_{\text{EV}} \cdot \exp[-\alpha_{\text{EV}} \cdot t - \beta_{\text{EV}} \cdot K - \varphi_B \cdot (1 - \text{SOH})]$$

$$D_i(t,K) = P_i - V_i(t,K)$$

α captures depreciation associated with age, obsolescence and factors that are not directly mileage-related; β captures value loss associated with use. For the EV, α and β describe the vehicle excluding the loss of value specifically attributable to battery SOH, which enters separately through φ_B ; this avoids counting battery ageing twice. For the ICE, β encompasses wear of the engine, transmission and the vehicle as a whole. There is no standardised 'engine cycle count' comparable with battery EFC: wear depends on mileage, engine hours, thermal starts, load and maintenance. It is therefore parameterised by mileage and calibrated against residual value rather than by inventing a universal mechanical life.

2.3. Battery degradation by calendar ageing and cycles

$$\text{SOH}(t,K) = 1 - d_{\text{cal}} \cdot t - [0.20 / N_{80}] \cdot \text{EFC}(K) \cdot s_{\text{charge}}$$

d_{cal} represents annual calendar loss; N_{80} is the reference EFC count to a 20% loss; and s_{charge} is a multiplier for charging pattern. The base scenario uses $d_{\text{cal}} = 1\%/ \text{year}$, $N_{80} = 2,500$ EFC and a multiplier of 1.70 for frequent high-power fast charging. This is a pedagogical calibration chosen to approximate orders of magnitude observed in real data, not a vehicle-model-specific forecast.

DOUBLE-COUNTING RULE

- SOH loss reduces the EV's residual value within D_{EV} ; it should not also be added as if every point of SOH were a cash payment.
- A new battery is added as an extraordinary cost only if there is a relevant probability of replacement within the horizon. If replaced, the residual value contributed by the new battery must also be increased.
- The same logic applies to the ICE: engine, gearbox, turbo or emissions-control systems are extraordinary risks, not certain marginal maintenance on every kilometre.

2.4. Financial or opportunity cost

The base opportunity cost is 5% per year. It is applied to the economic value of the capital that remains tied up, rather than as an arbitrary 5% surcharge on every expense.

$$F_i(t) = r \cdot \int_0^t V_i(s) ds$$

This formulation is equivalent to requiring an annual return on the capital still tied to the vehicle. The more expensive EV initially bears a higher financial cost, but the difference declines as the asset depreciates. With actual financing, r can be replaced by the effective borrowing cost or by an opportunity cost appropriate to the buyer's profile.

2.5. Cost of time

The base value of time is set at €15/hour. Only effective, non-overlapping time is monetised: detours, waiting, connection, disconnection or compulsory dwell time. Overnight charging while sleeping is not equivalent to eight lost hours. The comparison is symmetric: the ICE also requires a detour and refuelling time.

3. Illustrative base scenario

Parameter	Value
ICE price	€28,000
EV price	€34,000
Charger and installation	€1,600
Incentive	€0
Combustion	6.5 l/100 km at €1.55/l
EV	17 kWh/100 km
Home charging	€0.16/kWh
Slow public charging	€0.35/kWh
Fast public charging	€0.55/kWh
Value of time	€15/hour
Cost of capital	5% per year
Reference usable battery	60 kWh
Calibration N80	2,500 EFC to 80%
Battery calendar ageing	1% SOH/year
ICE calendar depreciation	$\alpha = 0.12/\text{year}$ (scenario)

EV calendar depreciation, net of SOH	$\alpha = 0.15/\text{year}$ (scenario)
ICE use-related depreciation	$\beta = 4 \times 10^{-7}/\text{km}$ (scenario)
EV use-related depreciation, excluding battery	$\beta = 2.5 \times 10^{-7}/\text{km}$ (scenario)
Residual-value sensitivity to SOH	$\phi_B = 0.50$ (scenario)
Fixed maintenance	ICE €320/year; EV €220/year
Average variable maintenance	ICE €0.032/km; EV €0.024/km
Other fixed costs	ICE €1,000/year; EV €1,070/year

HOW TO READ THE DEPRECIATION PARAMETERS

- α , β and ϕ_B are not presented as official Spanish averages. They are transparent parameters so that the model can be recalibrated using residual-value data for the specific model.
- The base scenario adopts somewhat higher time-related depreciation for the EV to reflect current obsolescence risk and lower retention observed in some markets; the IEA reports that BEV retention across five large European markets fell towards 35% in 2025, although those data are not adjusted for average age and should not be transferred mechanically to a specific car [7].
- The model's advantage is precisely that the result can be recalculated without changing its structure.

4. Entry price and acquisition trajectory

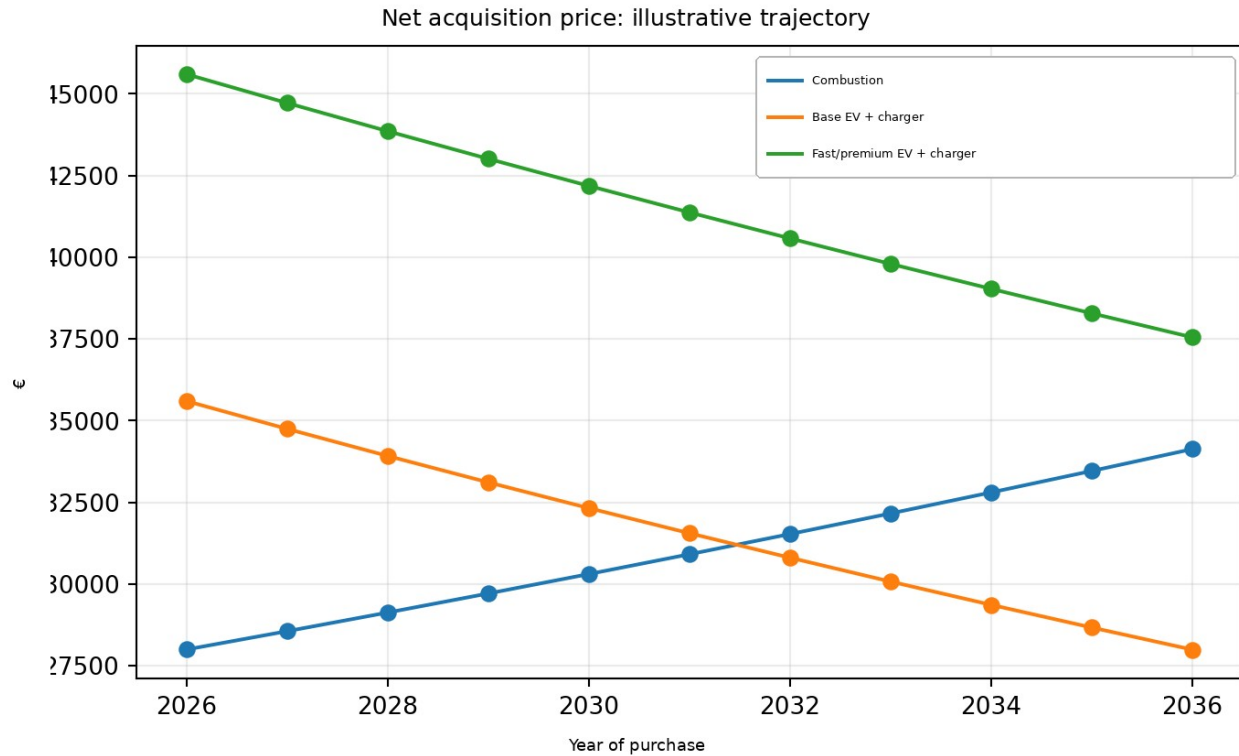


Figure 1. Illustrative entry-price trajectory.

QUICK READING

- This chart deliberately isolates acquisition. It is the only one that is not intended to be a TCO: it shows the capital premium that later generates depreciation and financial cost.
- Purchase-price parity is not required for the EV to be economically preferable; TCO can cross earlier.
- The trajectories are scenarios, not price forecasts.

5. Cumulative economic cost at 50,000 km/year

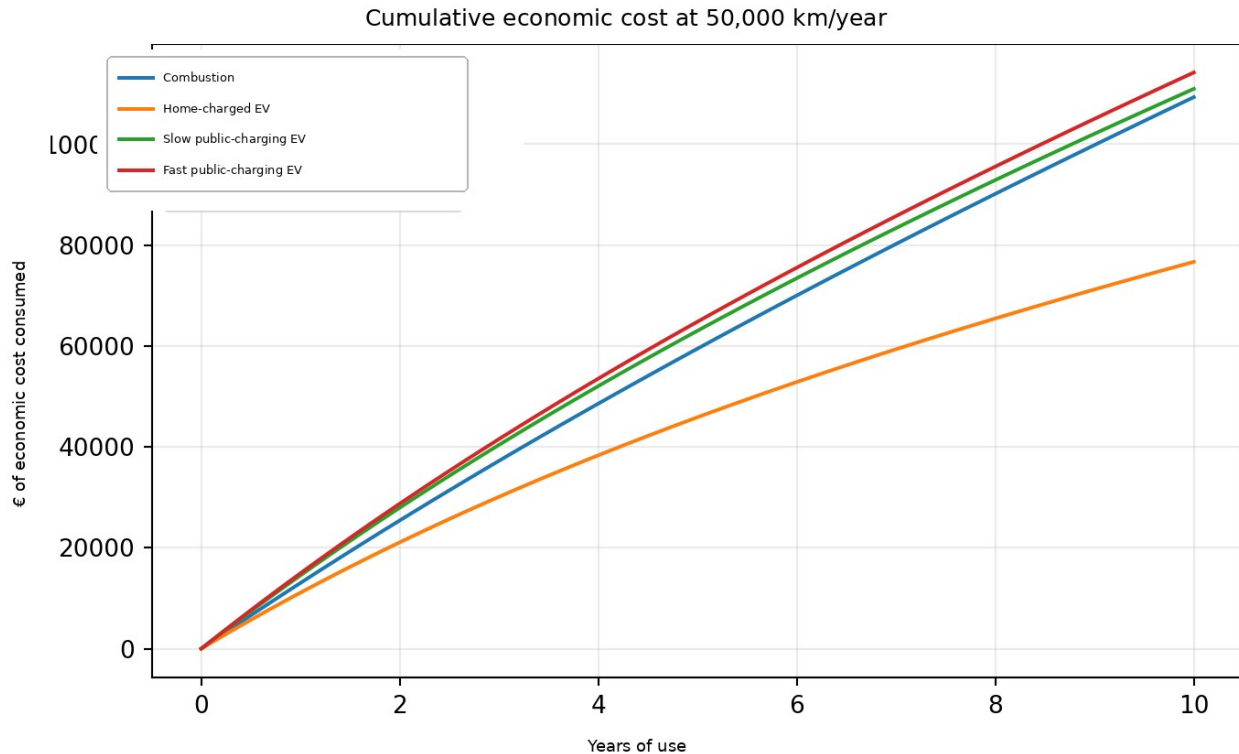


Figure 2. Economic cost consumed, including depreciation, financing and time.

QUICK READING

- The curves no longer simply add the full price as if it vanished at purchase: they account for the portion of capital consumed through depreciation and the financial cost of the remaining capital.
- With home charging, the EV has lower economic cost from the first year in the intensive-use example; however, cash payback of the initial premium occurs at around 2.0 years.
- With fast or slow public charging, the assumed prices and times can keep the ICE below the EV throughout the horizon shown.

6. Annual break-even kilometres

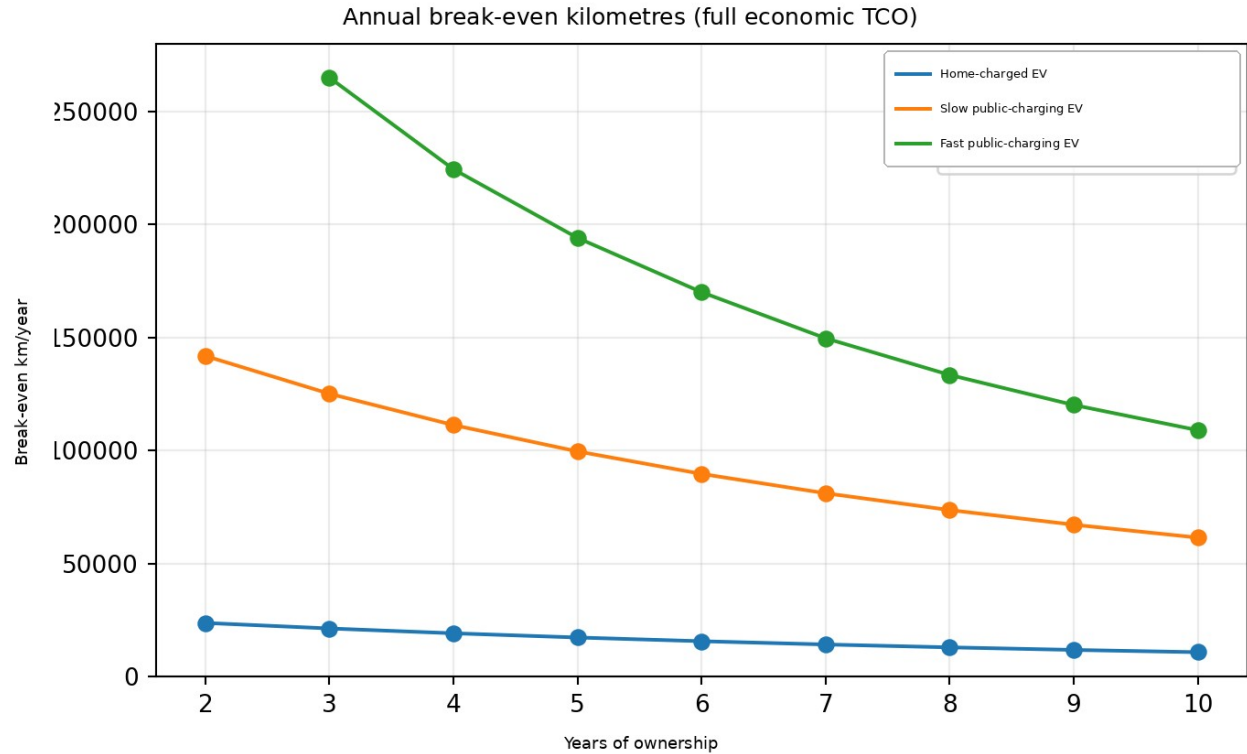


Figure 3. Annual utilisation required for EV economic TCO to equal ICE economic TCO.

QUICK READING

- At five years, the base home-charging threshold is approximately 17,200 km/year.
- The threshold falls as the horizon lengthens because energy and maintenance savings recur more times and capital costs are spread over a longer period.
- Expensive public charging shifts the frontier sharply, even when the EV has lower mechanical maintenance.

7. Value of charging and refuelling time

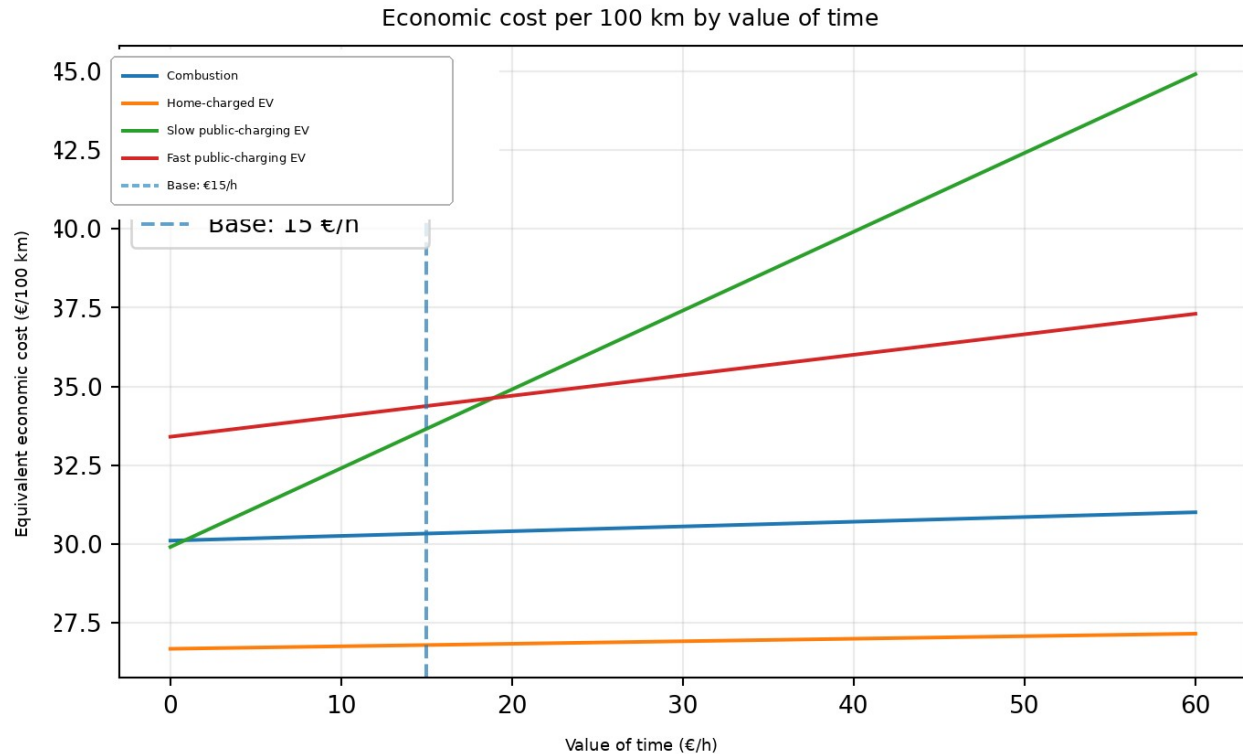


Figure 4. Equivalent economic cost per 100 km as the value of an hour changes.

QUICK READING

- The X-axis is the economic value of an hour, not gross charging duration.
- The vertical line marks the base scenario of €15/hour.
- The chart includes energy, maintenance, depreciation and financing over five years at 30,000 km/year; it therefore shows total equivalent cost, not only variable cost.

8. Economic advantage and lagged market share

Adoption does not react instantaneously to an improvement in TCO. Perception, financing, supply, charging networks, replacement cycles and technological aversion all intervene. The economic variable feeding the adoption model is full TCO, including depreciation and financial cost.

$$\text{Share\_EV,new}(t) = 1 / [1 + \exp(-(a + b \cdot A\_EV(t-L) + \gamma Z(t)))]$$

$$A\_EV = (G\_ICE - G\_EV) / G\_ICE$$

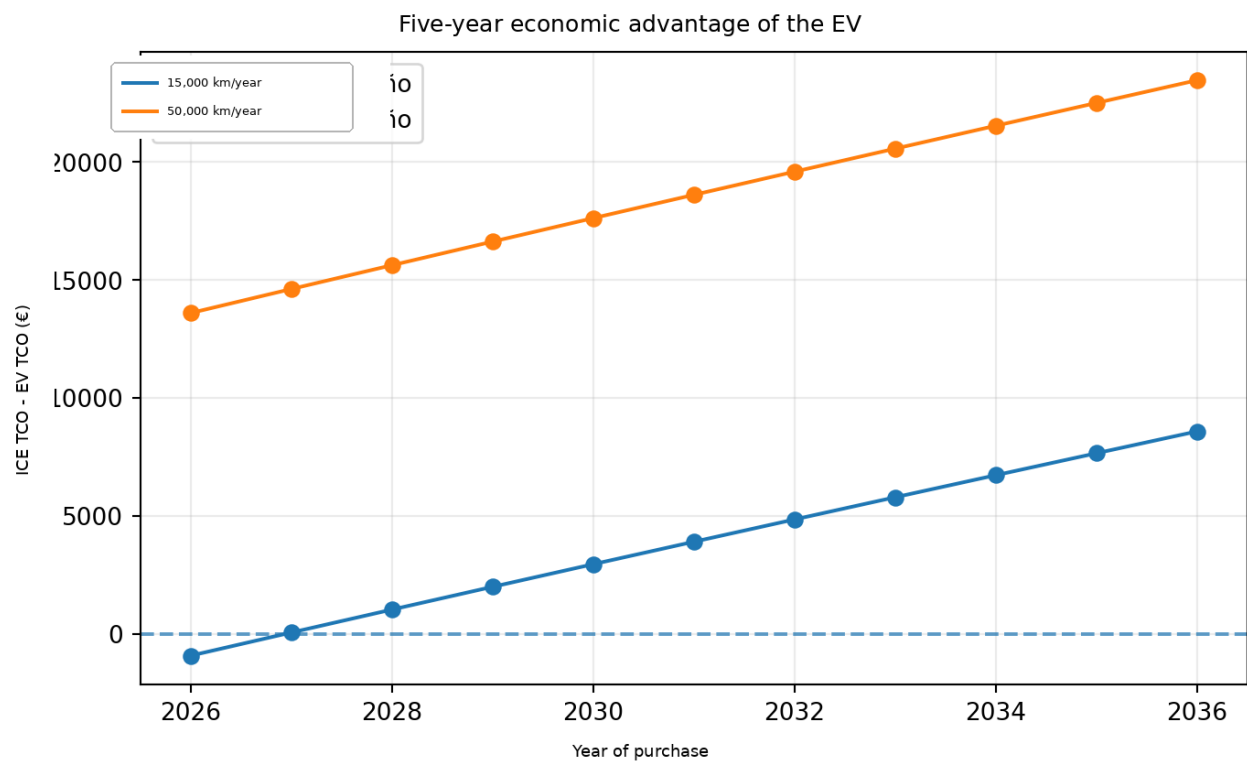


Figure 5. Five-year economic advantage of the EV by year of purchase.

QUICK READING

- Above zero, the EV has lower economic TCO.
- In the 15,000 km/year scenario, the crossover appears approximately between 2026 and 2027 because of the illustrative price trajectory; at 50,000 km/year the EV already has an advantage in 2026.
- Financial cost and depreciation are included in each five-year horizon.

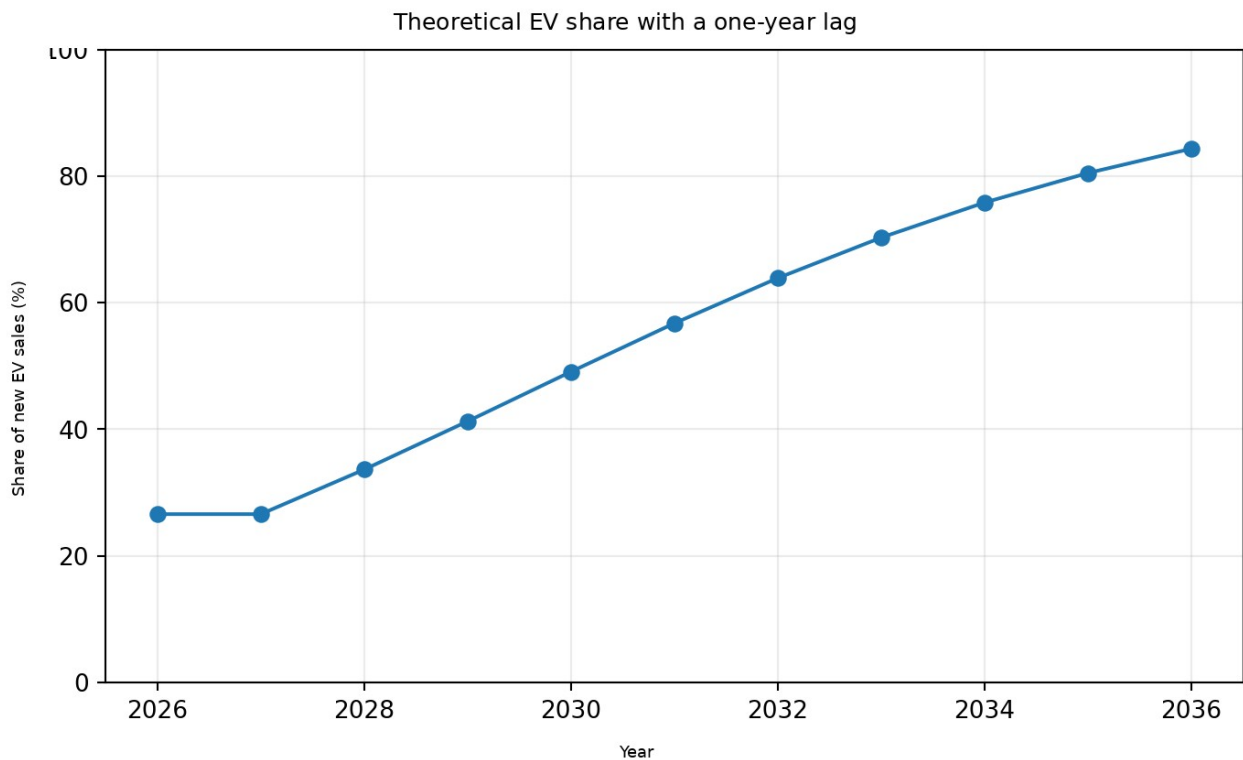


Figure 6. Theoretical EV share with a one-year lag relative to the economic advantage.

QUICK READING

- This is a demonstration of the mechanism, not an econometric forecast.
- The share of new sales reacts sooner than the share of the total vehicle stock.
- An empirical calibration should estimate a , b , L and the Z variables from real data.

9. Maintenance: time, use and event structure

These two figures deliberately isolate maintenance so that it can be interpreted. Depreciation and financing are not drawn inside a figure labelled 'maintenance', but they are reincorporated into every TCO and break-even chart.

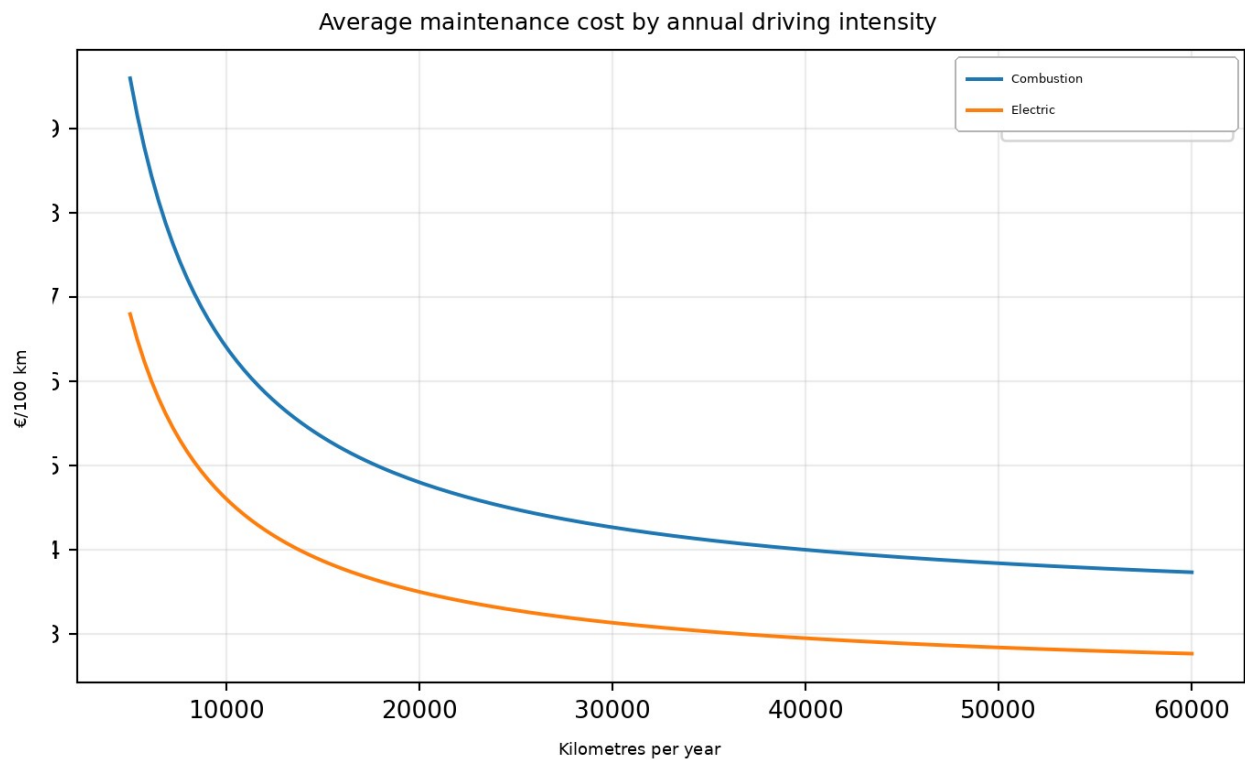


Figure 7. Average maintenance cost per 100 km by annual mileage.

QUICK READING

- Average cost falls with use because the annual component is spread over more kilometres.
- Marginal cost per kilometre does not disappear; the curves therefore converge towards a floor.
- The figures are scenario values and should be replaced with the maintenance plan, tyre costs and fleet experience of the specific vehicle.

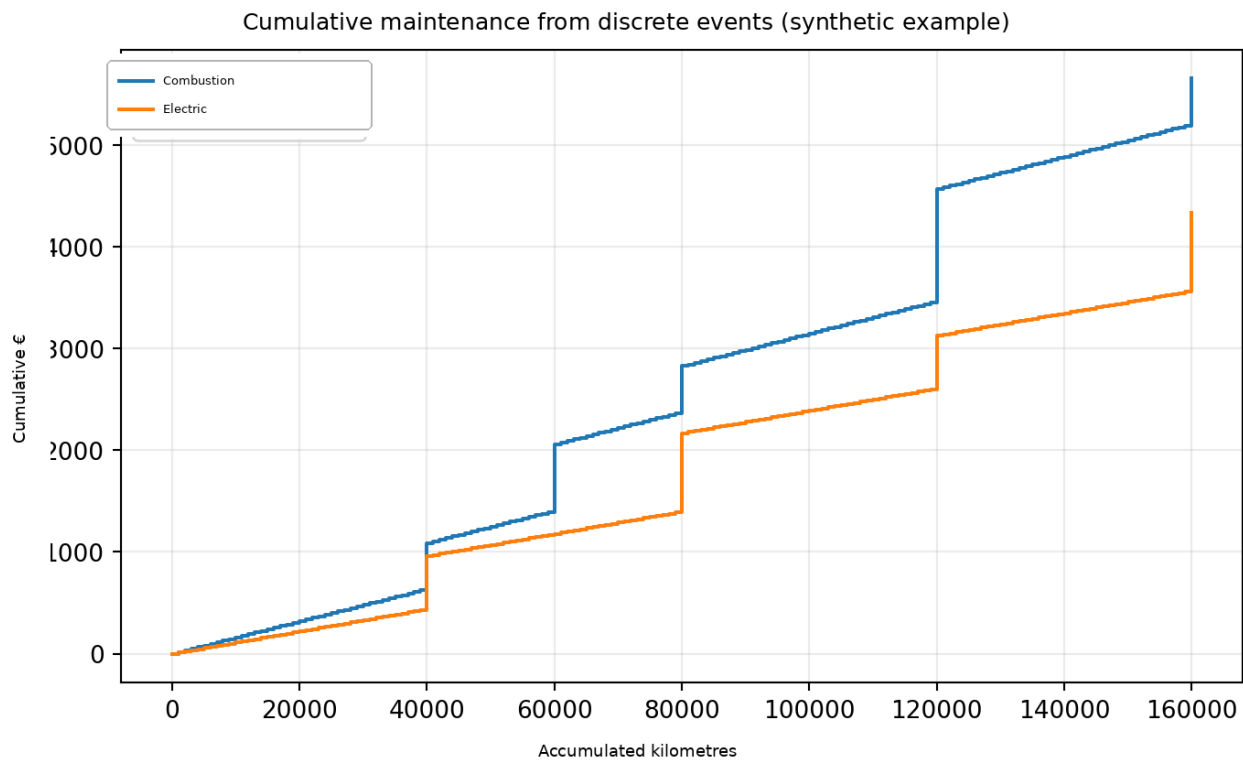


Figure 8. Synthetic example of maintenance payments from discrete events.

QUICK READING

- Actual cash expenditure is stepwise: servicing and tyres are paid at specific points.
- A straight €/km line is a long-run approximation, not a literal description of every kilometre.
- The steps shown are pedagogical and do not correspond to any manufacturer's maintenance schedule.

10. Break-even point in accumulated kilometres

The same model can be expressed by distance. If A is annual mileage, $t = K/A$. This makes clear that 100,000 km driven in two years is not economically equivalent to 100,000 km driven in ten: calendar ageing, fixed costs, financing and battery degradation all differ.

$$t = K / A$$

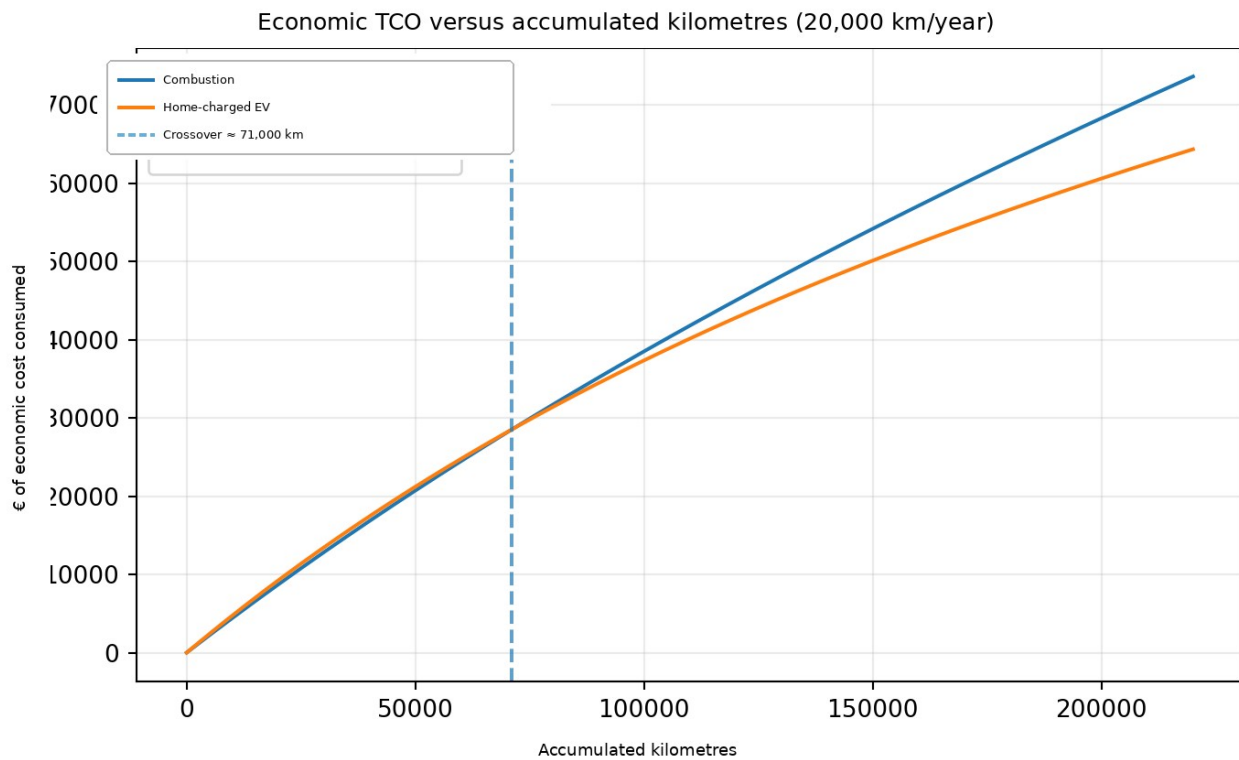


Figure 9. Economic TCO versus accumulated kilometres at 20,000 km/year.

QUICK READING

- The example crossover occurs at around 71,000 km.
- The axis incorporates energy, maintenance, age- and use-related depreciation, battery SOH, financing and time simultaneously.
- A change in km/year alters this curve because it changes how much calendar time passes before the same odometer reading is reached.

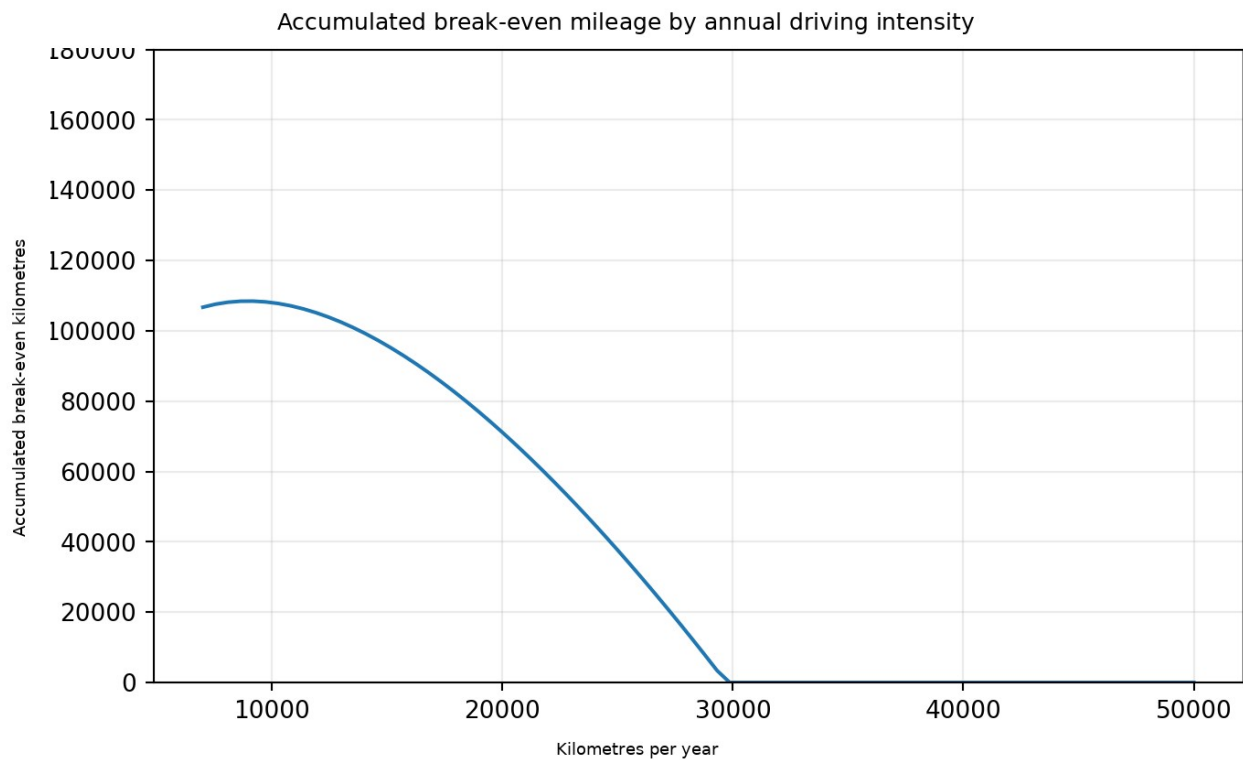


Figure 10. Accumulated break-even kilometres by annual utilisation intensity.

QUICK READING

- There is no single magic payback mileage.
- At low utilisation, the same mileage takes more years to reach and accumulates more time-related depreciation and fixed costs.
- At high utilisation, the EV can have an economic advantage almost from the start of service even though it still requires more cash at purchase.

11. Multidimensional substitution frontier

The decision can be represented as a frontier in a space of user characteristics. Access to cheap charging, mileage, the value of time, the cost of capital and depreciation are simultaneous variables rather than alternative explanations.

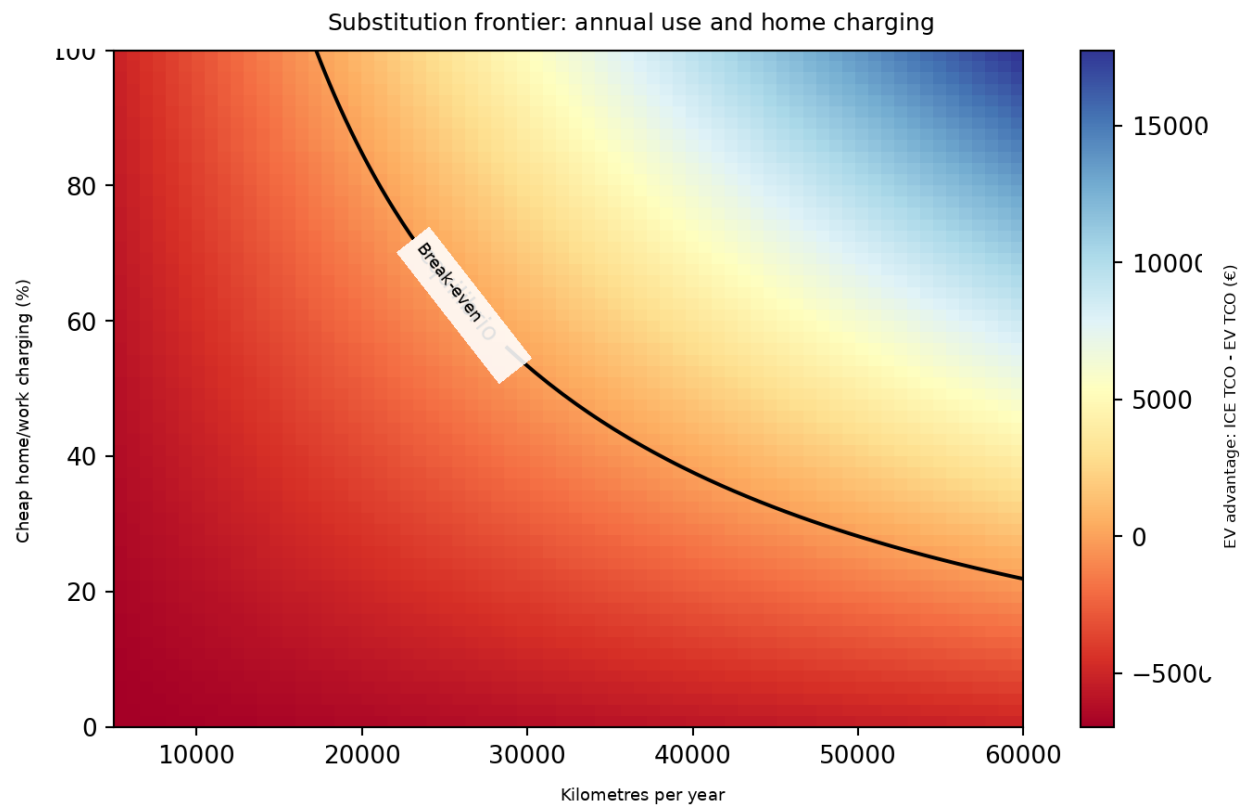


Figure 11. Five-year EV advantage by km/year and share of cheap home/work charging.

QUICK READING

- The black line separates combinations in which each technology has the lower TCO.
- More mileage and more low-cost charging tend to move the decision towards the EV.
- In the model, the public-charging share also affects battery degradation when it is associated with high power.

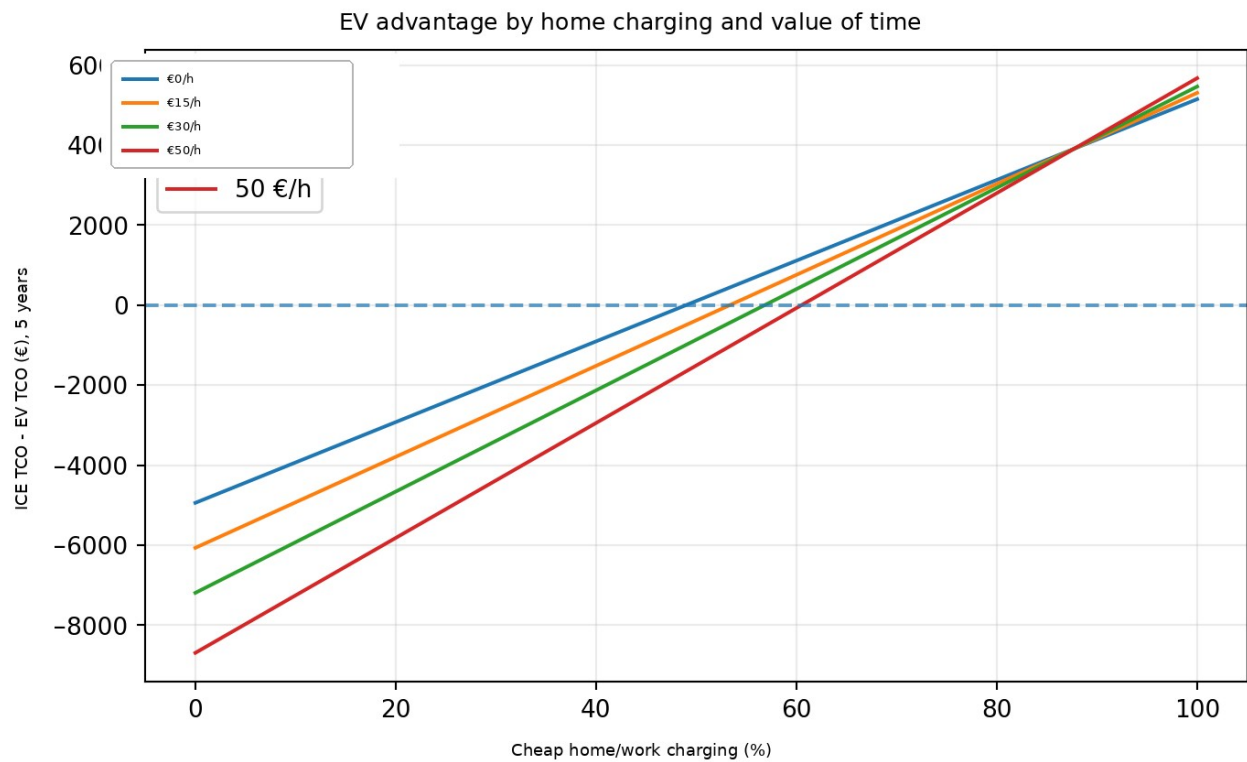


Figure 12. EV advantage at 30,000 km/year by home charging and value of time.

QUICK READING

- The base scenario is €15/hour.
- When charging overlaps with sleep or work, the effective time cost falls and the EV improves.
- A high value of time particularly penalises profiles dependent on public charging with compulsory dwell time.

12. Cost of capital, residual value and extraordinary risks

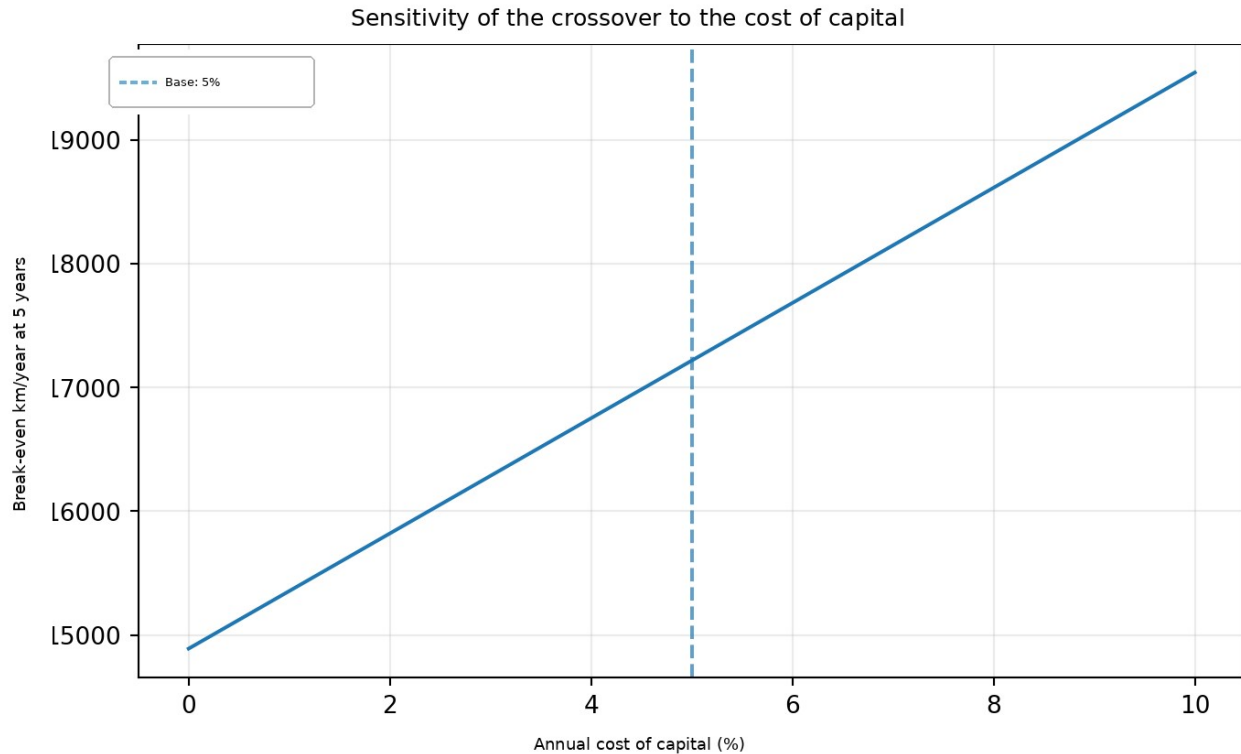


Figure 13. Effect of the cost of capital on the five-year threshold.

QUICK READING

- At $r = 0\%$, the home-charging threshold is approximately 14,900 km/year; at 5% it rises to about 17,200 km/year and at 10% to about 19,500 km/year.
- The EV's higher initial price makes opportunity cost relevant even when energy is cheap.
- A discount rate and an additional 5% should not both be applied to the same cash flows when they represent the same financial cost.

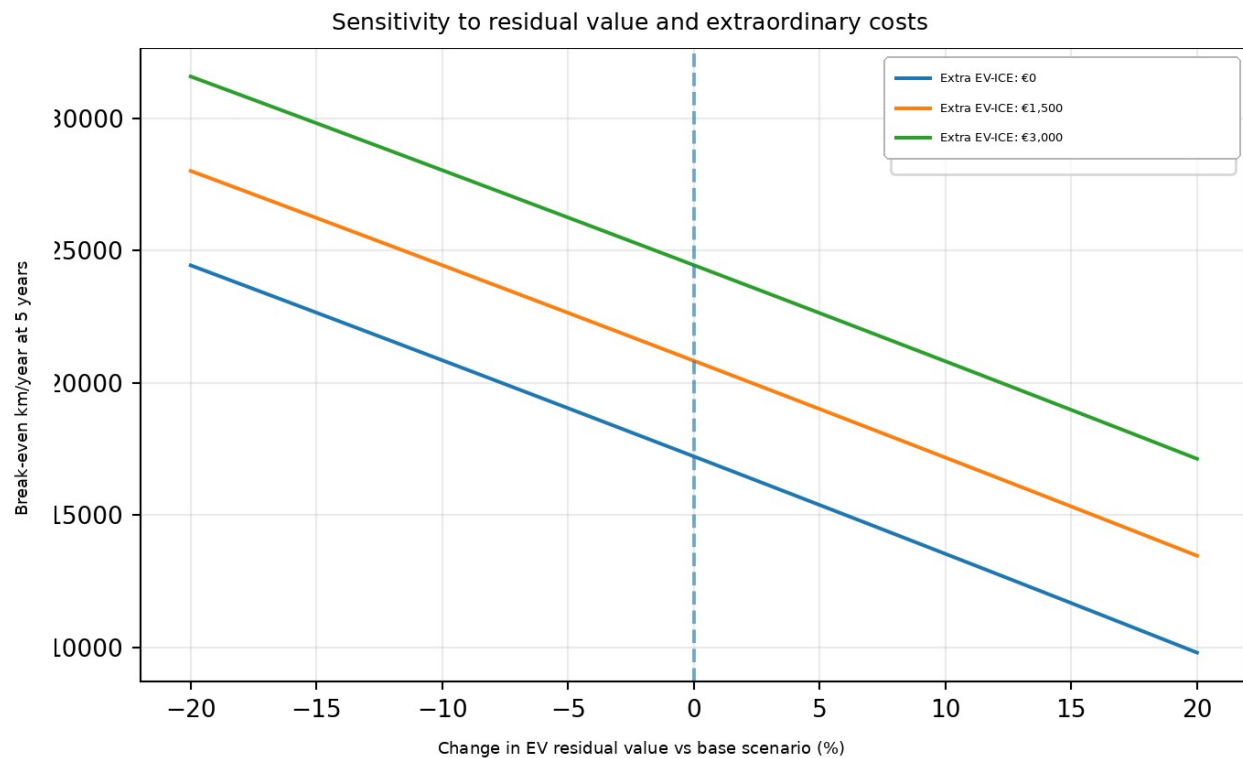


Figure 14. Sensitivity to residual value and net EV-ICE extraordinary costs.

QUICK READING

- A lower EV residual value increases the mileage required to compensate; a higher residual value reduces it.
- The extraordinary cost is differential: EV battery/repairs minus ICE engine/transmission/other repairs.
- Battery replacement at 70-80% SOH is not assumed; replacement enters only when it is probabilistically relevant within the horizon.

13. Battery-cycle-specific depreciation

The battery makes it possible to represent the use-related portion of depreciation explicitly. The same mileage can imply a different state of health depending on elapsed years and charging power. The following figure uses the base parameters; it is not intended to describe every battery pack.

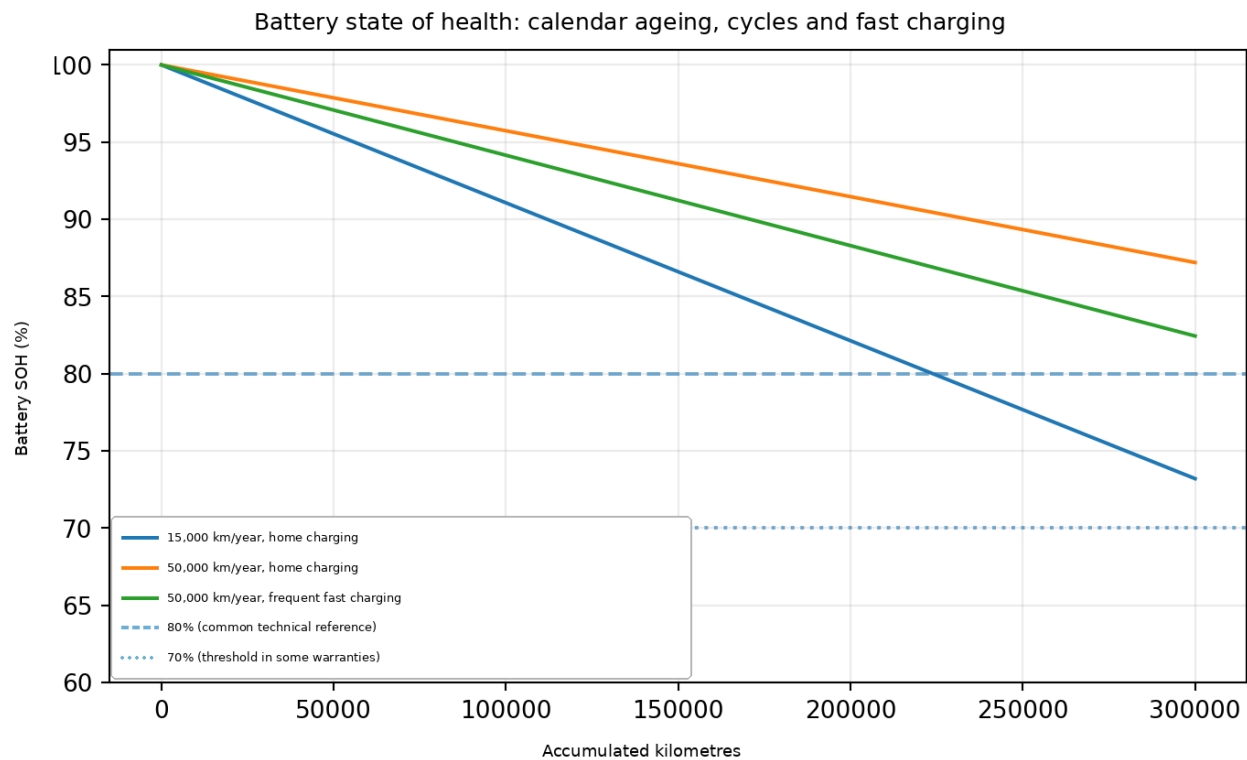


Figure 15. Battery SOH versus accumulated kilometres for different utilisation intensities and charging patterns.

QUICK READING

- For the same mileage, accumulating it slowly over many years can produce more calendar ageing.
- For the same years and mileage, frequent fast charging increases the cycle-degradation component in the scenario.
- 80% and 70% are useful references, but they do not mean a 'dead battery'. Euro 7 and manufacturer warranties confirm that durability is expressed as remaining capacity, not as an automatic replacement obligation.

ORDER OF MAGNITUDE OF CYCLES

- 15,000 km/year $\approx$ 42.5 EFC/year with 60 kWh and 17 kWh/100 km.
- 50,000 km/year $\approx$ 141.7 EFC/year.
- Over eight years at 50,000 km/year, the base home-charging model gives $\approx$ 82.9% SOH; with frequent fast charging $\approx$ 76.6%.
- 10,000 EFC would represent $\approx$ 3.53 million km; this is why it is not used as the base life of a passenger car.

14. Cost of capital per kilometre: why intensive use changes the decision

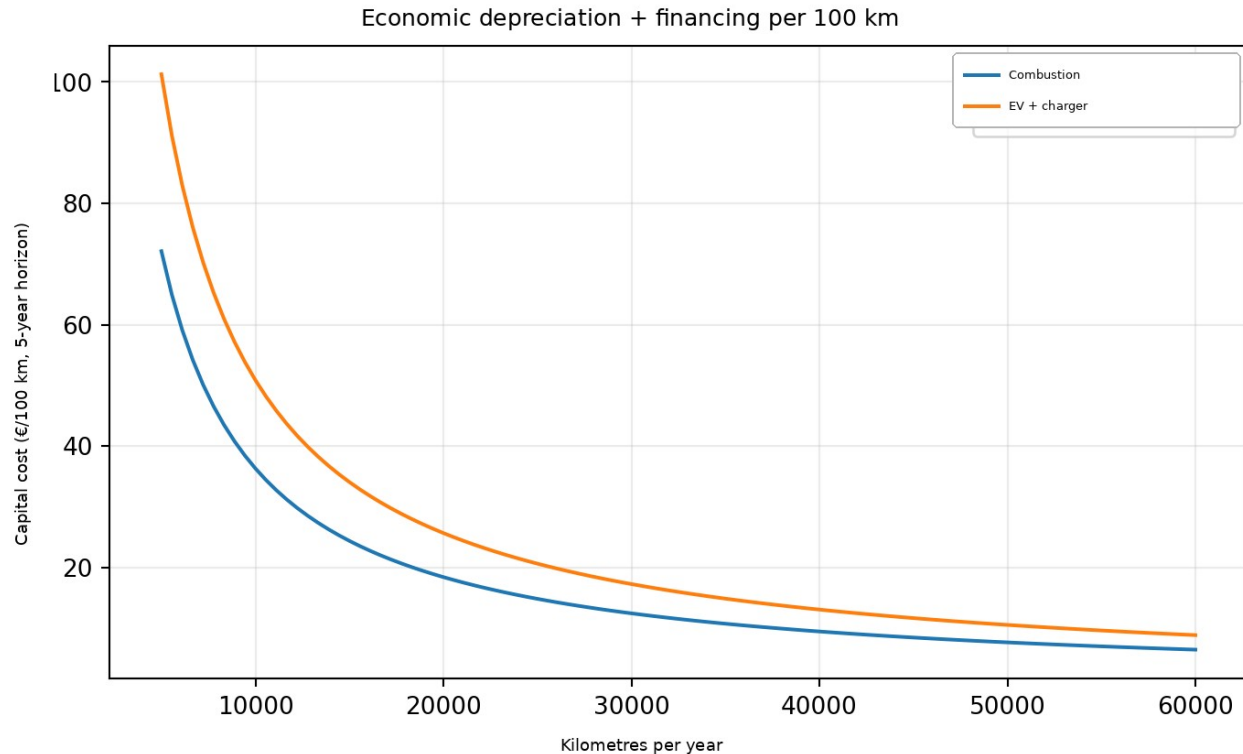


Figure 16. Economic depreciation + financing per 100 km over five years.

QUICK READING

- At low mileage, calendar value loss and financial cost are spread over little distance and therefore weigh heavily per 100 km.
- As utilisation rises, the fixed capital component is diluted, although mileage- and cycle-related wear increases.
- This figure formalises the intuition that average cost per km depends on annual mileage even when marginal energy cost does not change.

15. Economic segmentation

Profile	Model reading
Urban private user with garage	Cheap charging and almost zero effective time; at low mileage, depreciation and capital weigh heavily.
Private user without a garage	More sensitive to public-charging price, waiting time and fast charging; the frontier may favour the ICE.

Salesperson / self-employed, 50,000 km/year	Energy savings multiply and fixed capital is diluted; charging availability must be monitored.
Taxi / ride-hailing / delivery	Highly sensitive to unproductive time, charging power, battery condition and value of an hour.
Frequent long-distance travel	Charging power and the opportunity cost of time can dominate maintenance.
Used-EV purchase	Certified SOH and residual value are especially relevant; odometer and age alone are not sufficient.

16. Sensitivity: what moves the crossover

Variable that increases	Typical effect on EV	Movement of crossover
Fuel price	Improves EV operating savings	Earlier / fewer km
Home electricity price	Reduces EV savings	Later / more km
Fast public charging	Raises energy, time and possible degradation	Later
Annual mileage	Dilutes fixed capital and multiplies energy savings	Earlier
Initial EV price	Increases depreciation and financing	Later
Cost of capital	Penalises the larger amount of tied-up capital	Later
EV time-related depreciation	Reduces residual value	Later
Better cycle life / SOH	Improves battery residual value	Earlier
Value of time	Penalises the mode with more effective time	Depends on pattern

Net EV extraordinary cost versus ICE	Raises expected EV TCO	Later
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17. How to apply the model to two real cars

1. Enter actual net prices, including charger, installation, incentives and financing conditions.
2. Measure real consumption for both vehicles and effective energy prices by charging/refuelling channel.
3. Set km/year, ownership horizon and the shares of home, workplace, slow public and fast public charging.
4. Obtain the actual maintenance and tyre plan; separate annual, per-km and event-based costs.
5. Estimate the value of time. Keep €15/hour as the base if no better estimate is available and analyse sensitivity.
6. Estimate residual value by age and mileage. For a used EV or a long ownership horizon, incorporate battery SOH when a reliable diagnosis is available.
7. Calibrate α and β using second-hand-market data for the specific model; do not treat the illustrative parameters dogmatically.
8. For the battery, convert kilometres to EFC from usable capacity and consumption; select N80 by chemistry/model when reliable information is available.
9. Use $r = 5\%$ as the base or replace it with the relevant APR/effective financing cost or opportunity cost.
10. Add extraordinary costs as expected values rather than certain replacements, and do so symmetrically for EV and ICE.
11. Calculate cash payback and economic TCO separately; they answer different questions.
12. Repeat thresholds at 3, 5, 8 and 10 years and construct the km/year $\times$ charging access $\times$ value-of-time frontier.

18. Conclusions

The comparison between electric and combustion cars should be understood as the cost of obtaining mobility services from an asset, not as a simple sum of purchase price and fuel. A vehicle loses value both with time and with use; in addition, tied-up capital has an opportunity cost. These two elements can materially change the break-even point, especially for low-mileage users.

For the ICE, use-related wear is modelled through mileage because there is no universal cycle metric equivalent to the battery. For the EV, the battery allows deterioration to be split between calendar ageing and EFC, but 70-80% SOH should not be confused with failure or mandatory replacement. The economic cost of degradation appears first as lower capacity and lower residual value; replacement should only be added as an expected extraordinary risk when it is plausible within the ownership horizon.

Under the report's base scenario -5% cost of capital and a €15/hour value of time- the EV advantage is concentrated particularly in intensive use and cheap home/work charging. The same technology may be clearly preferable at 50,000 km/year and fail to outperform the ICE for low use dependent on public charging. The relevant result is therefore neither a single 'parity year' nor a single 'payback mileage', but a multidimensional frontier of economic substitution.

19. Sources and references

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FINAL METHODOLOGICAL NOTE

- External sources justify mechanisms, regulatory thresholds and orders of magnitude. Prices, α , β , ϕ_B , N80 and other numerical scenario parameters are adjustable and are not presented as a universal official average.
- Proper calibration for an actual decision consists of replacing scenario parameters with data for the specific model, use case and second-hand market.